

Experimental discovery and verification of the third type of DC gas flow in pulse tube cryocooler

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ABSTRACT

DC gas flow in pulse tube cryocooler (PTC) is a crucial problem both in theory and application which considerably affects the refrigeration performance. We have experimentally discovered and verified the third type of DC gas flow in PTC which is formed due to hydrodynamic and thermodynamic asymmetry of the regenerator and other flow channels. This new type of DC gas flow is possible to be identified in other regenerative engines or refrigerators. We also introduced a highlighting method which can suppress this kind of DC gas flow effectively in most cases, with the best result of 30 K temperature drop at the cold end of the PTC.

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1. Introduction

Pulse tube cryocooler (PTC) is a small-scale regenerative refrigerator without any moving components at cryogenic temperature. So it has great potential for a wide range of applications such as aerospace, communication and superconductivity. G-M type PTC working at low frequency can easily reach 4.2 K. However, until recently, single stage Stirling type PTC cannot attain liquid helium temperature, while PTC working at higher frequency (above 100 Hz) is difficult to reach 20 K [1]. The third type of DC gas flow we discovered in PTC may be one of the key reasons why it is more difficult to obtain low temperature at higher frequency. Moreover, this paper presents a simple but elegant way eliminating this type of DC gas flow which is promising to make high frequency PTC to be much more efficient and capable of reaching lower temperature.

The working fluid inside PTC is characterized as the oscillating (AC) gas flow, which moves alternatively backward and forward with pulsating pressure at certain frequencies. When a thermodynamic cycle of the oscillating flow is done inside PTC including the appropriately placed regenerator and heat exchangers, heat can be pumped from low temperature consuming compressor work. Nevertheless, compared with the main oscillating gas flow, it is widely accepted that there are two types of DC gas flow in PTC called Gedeon [2] and Rayleigh [3] DC gas flow. Gedeon DC gas flow is caused by a closed-loop flow path which exists in the double-inlet pulse tube refrigerator, connecting the pulse tube to

the regenerator by the double-inlet valve. In addition, Rayleigh DC gas flow is acoustic streaming which is caused by the difference of viscosity of gas parcel through the pulse tube in the boundary layer. DC gas flow carries heat away from the hot heat exchanger and deposits it at the cold end, creating an additional heat loss,

$$\dot{Q}_{\text{loss}} = \dot{M}_2 c_p (T_h - T_c), \quad (1)$$

where c_p is the constant pressure heat capacity of the helium. Although the magnitude of the mass flow of DC gas flow is small, the additional heat carried by it is on the same order of the theoretical refrigeration power of PTC, which significantly degrades cooling performance and deteriorates refrigeration temperature stability of PTC. Besides PTC, main oscillating flow accompanied with secondary DC flow is a unique physics phenomenon in different kinds of heat engines and refrigerators, especially for thermoacoustic engines [4]. Hence it makes great sense to identify and suppress DC gas flow in regenerative devices.

2. Theoretical analysis

So far, only Gedeon [5] and Rayleigh [3] DC gas flows are observed in experiments. Pressure drops due to eddies at entrances and exits in regenerator are asymmetrical with the direction of flow, with the degree of asymmetry dependent on the Reynolds number and geometric details. As a result of the asymmetry of pressure drops in regenerator, DC gas flow will be generated as the time averaged mass flow rate is different between one direction during half a cycle and the opposite direction during the next half cycle. To make it clear, we can make the Darcy flow

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assumption for flow through porous materials, such as a regenerator matrix. Moreover, we consider sinusoidal fluctuation of pressure drop and density,

$$\xi = \xi_0 + \xi_1 \sin \omega t, \quad (2)$$

where ξ represents pressure drop or density, subscripts 0 and 1 represent orders of variables. Thus the time averaged DC flow rate is

$$\dot{M}_2 = \rho_0 \Delta p_0 + (\rho_1 \Delta p_1 \cos \alpha) / 2, \quad (3)$$

where $\dot{M}_2$ is time averaged mass flow rate, ρ is density, Δp is pressure drop, α is phase angle between pressure drop and density. This equation indicates that where there is asymmetrical pressure drops in regenerator, there may be DC gas flow [2]. Due to the asymmetrical flow resistances, the imbalanced mass flow will gradually accumulate in the side of cold end of the regenerator, causing increase of average pressure of the “gas displacer” in the pulse tube. While the average pressure exceeds a critical value, mass flow will transport from the warm end of the pulse tube to the cold end of the pulse tube, the regenerator, and the compressor. Hence there will be pressure gradients along the refrigeration system after the new balance is formed.

The theoretical analysis above is similar to Gedeon DC gas flow. But there are two crucial differences from it which should be emphasized here: first, there is no closed-loop in PTC without double-inlet bypass orifice which is the key structure for Gedeon flow. Second, this pressure drop effect will accumulate in PTC and turn out to be the DC mass flow at a critical point. Fig. 1 is a schematic drawing of this new type of DC gas flow in PTC.

According to this intrinsic physics mechanism and from peculiar phenomena discovered in ultra-high frequency PTC, we have theoretically analyzed a new type of DC gas flow in PTC [6] without any closed-loop induced by double-inlet design and of minor influence by Rayleigh streaming in the boundary layer, which is totally different from the two demonstrated types mentioned above or any other streaming predicted through numerical simulation [7] before.

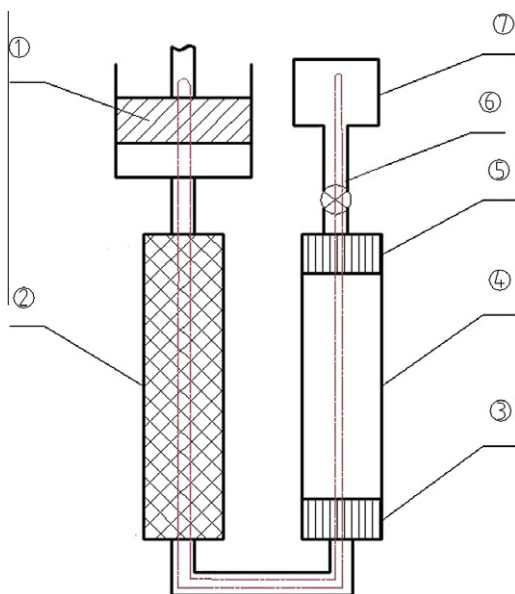


Fig. 1. Schematic drawing of the third type of DC gas flow in PTC for theoretical analysis. The close loop represents the DC flow, and ① compressor ② regenerator ③ hot heat exchanger ④ pulse tube ⑤ ambient heat exchanger ⑥ phase shifter (orifice or inertia tube) ⑦ reservoir.

3. Experimental discovery and verification

In order to verify our theoretical prediction, we have done a series of experiments of PTC. We use two different linear compressors to drive PTC for comparison with each other. C1 is a dual piston compressor while C2 is a single piston one. We use two types of coaxial orifice PTC with a volume adjustable reservoir. The only difference between PTC 1 and PTC 2 is the latter one has a second stage. The schematic configuration is shown in Fig. 2 and the geometrical detail is shown in Fig. 3. Our first step is to measure the average pressure of the reservoir and the back pressure chamber (BPC) of the compressor. The metering valve in Fig. 2 which connects the BPC of the compressor to the reservoir is shut off all the time at this stage; hence the PTC system is a common one in which there is no closed flow path. Table 1 clearly shows that there is obvious pressure difference between the reservoir and the BPC of the compressor. Under most circumstances the average pressure of the BPC is higher than the reservoir as shown in Table 1. However, sometimes the pressure drops have the reverse direction in our experiments. This coincides with the argument that DC gas flow is highly erratic and unstable which is also discovered in experiments before [8].

In principle, all of the flow passages of the PTC tend to produce DC biases, but the regenerator is the key component due to its asymmetric entrance and exit effect. Thus the inflow mass and outflow mass of the regenerator are not equal to each other in one cycle, mainly because of the characteristic of oscillating flow, asymmetry of the structure and different local loss of resistance in the refrigeration system [6]. As a matter of fact, average pressure drops between the reservoir and the BPC of the compressor represent the accumulating effect of hydrodynamic and thermodynamic asymmetry of the refrigeration system, and especially the regenerator. Though zero order pressure drops have shown the cumulative process clearly, first order pressure drops and phase angle between pressure drop and density are needed to determine DC gas flow from Eq. (3). However, previous research always considered pressure in the BPC of compressor and the reservoir as constant and has never realized the significance of one order pressure. Fig. 4 shows the diagram of oscillating pressure wave in both the BPC

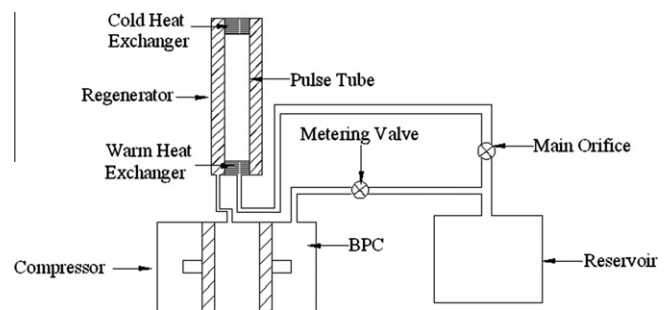


Fig. 2. Schematic configuration of PTC system used in the experiments.

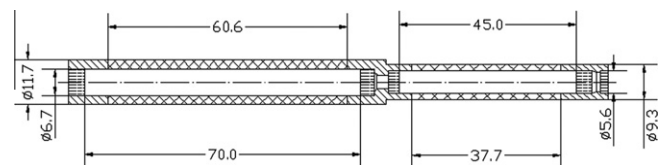
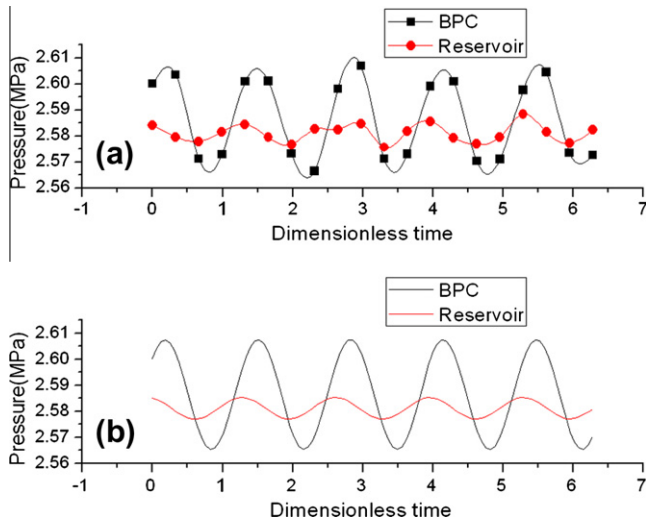


Fig. 3. Geometric dimensions of PTC 2. The left half part of Fig. 2 is PTC 1 with length of 70 mm. Volume of PTC 1 is 2.18 cc, with regenerator of 3.94 cc. Volume of PTC 2 is 3.10 cc, with regenerator of 5.57 cc.

Table 1

Representative measurements of average pressure difference between the reservoir and the BPC of compressor at a certain performance.

Compressor	PTC	Frequency (Hz)	Power (W)	Cold head temperature (K)	Average pressure of BPC (MPa) P_1	Average pressure of reservoir (MPa) P_2	Δp (MPa) $P_1 - P_2$
C1	PTC 2	59	145.6	91.7	2.548	2.574	-0.026
C1	PTC 2	59	140.7	90.3	2.550	2.532	0.018
C2	PTC 1	38	101.1	103.6	2.522	2.512	0.010
C2	PTC 2	39	129.2	95.9	2.584	2.532	0.052

**Fig. 4.** Diagram of oscillating pressure wave in the BPC of compressor and the reservoir in C1 and PTC 2. (a) Experimental measurements. (b) Fitted curve.

of the compressor and the reservoir. Since $\rho \propto p$, phase angle between ρ and Δp is identical to p and Δp . Hence we can estimate $\dot{M}_2$ approximately from Fig. 4 and obviously it is non-zero. By now we can conclude that the third type of DC flow really exists in PTC.

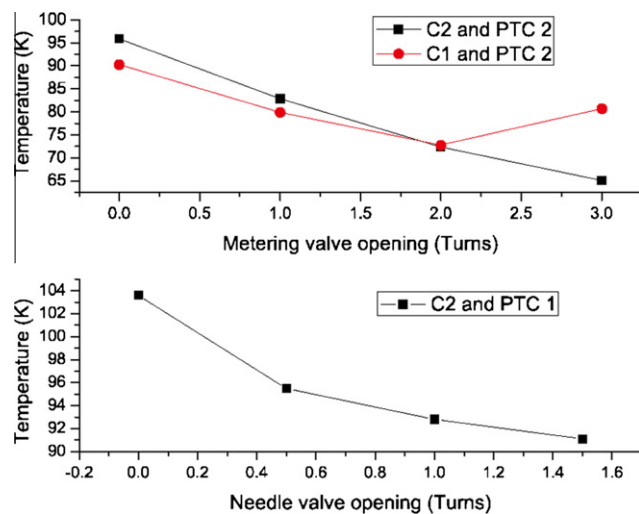
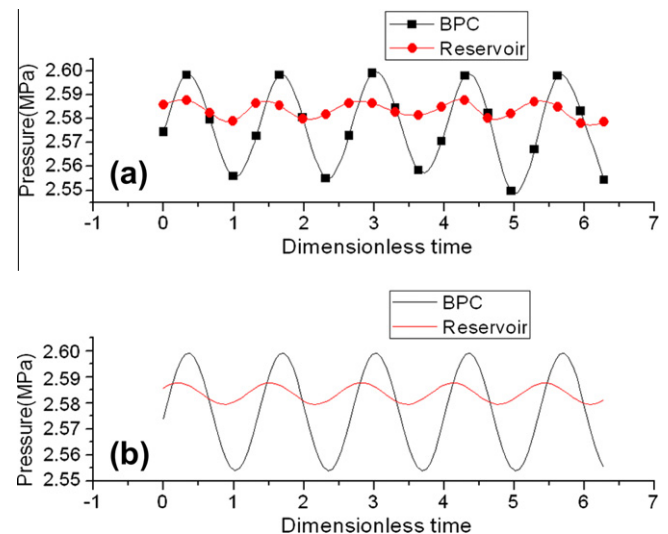
The more direct method to demonstrate the validity of our theory is to see whether there is any effect upon refrigeration temperature after eliminating this new type of DC gas flow in some way. Thus we open the metering valve which connects the BPC of the compressor to the reservoir after PTC reaches its lowest tempera-

ture. It is an important innovation but as simple as possible. In all the experiments when the average pressure of the BPC of the compressor is higher than the reservoir, it obviously has a positive effect for improving refrigeration performance. Fig. 5 shows the lowest cooling temperature of different turns of the metering valve of the two types of PTC driven by two different compressors. The largest temperature drop is 30 K which indicates the significant effect after opening the valve to balance pressure drops. With various compressor and PTC types, the effect of this innovation is different due to system coupling optimization and different DC gas flow effect. The only exception is the case in which the average pressure of the BPC of the compressor is lower than the reservoir due to instability of DC gas flow. From Eq. (3), we need a pressure drop to suppress the new DC gas flow.

$$\rho_0 \Delta p_0 = -(\rho_1 \Delta p_1 \cos \alpha) / 2. \quad (4)$$

In that case, a reverse pressure drop is needed to balance the DC gas flow [4]. Hence the method is not appropriate here and novel ideas are needed to suppress this unstable third type of DC gas flow. Nevertheless, all these results verify that the DC gas flow exists in the oscillating flow system. Fig. 6 shows the diagram of oscillating pressure wave in both the BPC of the compressor and the reservoir after opening the metering valve to the optimum turns. By comparing sine fitted curve Fig. 4b with Fig. 6b, it shows 0.012 MPa change of average pressure drops and 28° change of phase shift angle between the two oscillating pressure waves. From Eq. (3), we can conclude that after opening the metering valve, the third type of DC gas flow is suppressed by changing both the zero and first order pressure drops through the refrigeration system.

Under optimum circumstance, the third type of DC gas flow is entirely eliminated. In that case, we can estimate the mass rate

**Fig. 5.** Cold end temperature after opening metering valve to a certain turns. (a) Experiments results for C2 with PTC 2 and C1 with PTC2 using a metering valve. (b) Experiments results for C2 with PTC 2 and C1 with PTC2 using another needle valve.**Fig. 6.** Diagram of oscillating pressure wave in the BPC of compressor and the reservoir after opening metering valve to optimum turns in C1 and PTC 2. (a) Experimental measurements. (b) Fitted curve.

of the DC gas flow approximately using the flow coefficient definition of metering valve.

$$C_v = 1.167 \dot{M} \sqrt{\frac{\rho}{\Delta p}} \quad (5)$$

In our experiments of PTC 2 and C1, for instance, 2 turns is for lowest temperature and corresponding C_v is 0.0003. Assume ρ to be constant at 300 K, so when $p = 2.5$ MPa, $\rho = 3.6$ kg/m³, and $\Delta p = 0.018$ MPa. Thus we can get $\dot{M}$ is approximately 1.8×10^{-6} kg/s. Furthermore, assume c_p of helium to be 5.2×10^3 J/kg, $T_h = 300$ K and $T_c = 70$ K, then from Eq. (1), we can estimate the heat loss carried by the third type of DC gas flow is 2 W. It is obvious that the DC flow magnitude is really small but has substantial influence on refrigeration performance.

4. Conclusions and discussion

For Stirling cooler with a real displacer, only a small amount of the third type of DC gas flow will occur in a limited region due to the displacer. Hence, influence on the refrigeration performance and temperature stability will be difficult to be observed. But for PTC with “gas displacer”, mass and interior pressure of “gas displacer” is changing with time. As the maximum oscillatory displacement of gas parcel is not large especially at ultra-high frequencies, it costs a long time for the average pressure of the system behind the cold end of the regenerator to reach the critical value and return to the average value of overall system. Hence the entrance and exit asymmetry in regenerator is stronger and the DC gas flow effect is more obvious. This phenomenon is discovered in our previous experiments [6] and now verified and explained clearly.

Another point of our research is to optimize a PTC for suppressing all kind of DC flows. As hydrodynamic and thermodynamic asymmetry of the regenerator and other flow channels in the

refrigeration system has a great influence on Gedeon flow and the third type of DC flow, controlling flow resistance is of great importance, especially for the regenerator. For instance, do not fill too many mesh screens in the regenerator and heat exchangers.

In summary, the third type of DC gas flow in PTC was verified by measuring zero and first order of pressure drops between the BPC of the compressor and the reservoir. We also made an innovation to suppress the DC gas flow successfully most of the time. Our next step will focus on mechanism and universal suppression method of the third type of DC gas flow in ultra-high frequency PTC and thermoacoustically driven refrigerator.

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